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THE CALCULATION OF CLOUD SHADOWS IN MODELING OF THE EARTH'S SURFACE FROM SPACE SURVEY

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Translation of "Raschet teney oblachnosti pri modelirovanii kosmicheskoy s"yemki zemnoy poverkhnosti," Meteorologiya i gidrologiya, No. 4, April 1974, pp. 37-42

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16. Abstract

An analytical formula is presented in the article which describes the relations between sporadic cumulus cloud coverage of the earth's surface, sun height and additional coverage by cloud shadows and area which can be inspected. It is found that a sun height of about 40-45° is the optimum for surveys of earth resources from a sun-synchronous satellite.

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ANNOTATION

In the article, an analytical formula is derived, which describes the relations among coverage by sporadic cumulus clouds, sun height and additional coverage by shadows cast by the clouds. Based on this, a sun height of about 40-45° is optimized for a survey of natural resources from a sun-synchronous satellite.

THE CALCULATION OF CLOUD SHADOWS IN MODELING OF THE EARTH'S SURFACE FROM SPACE SURVEY

B. V. Vinogradov and A. B. Vinogradov

In a space survey of the earth's surface, cloudiness is the /37* second factor (after illumination) maintaining the possibility of obtaining an image of the earth's surface in the optical range. The effect of cloud masking on ability to examine the earth's surface has been established repeatedly by a number of investigators, based on the space-frequency and time-frequency distribution functions of cloud cover over the earth [1-4]. However, only the projective cloud cover has been included in calculations, and the presence of shadows cast by clouds has not been taken into account.

For an approximate solution of the problem of calculating the effect of shadows cast by clouds on ability to examine the earth's surface, we have analyzed a target characterizing the shape of sporadic cumulus cloud cover. To calculate the additional target coverage, as a consequence of shadows from cloud cover, a formula can be derived, describing the relation between the projective cloud cover, sun height over the local horizon and the probability of coverage of the earth's surface by cloud shadows. In the derivation of this formula, cloudiness was approximated, in the form of a random distribution of equidimensional and isometric clouds of various degrees of coverage. The horizontal cloud shape was approximated, in turn, in the form of a circle, and the vertical cloud shape and outline of the shadow cast, in the form of a semiellipse. Based on these simplifications, we derived the following formula for calculation of the additional target coverage, as a consequence of shadows from cloud cover on the earth's surface:

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* Numbers in the margin indicate pagination in the foreign text.

$$S_{+} = S_0\Big[(\sigma L - \sigma L\,\sigma N + \sigma N) - 2M\sqrt{M - \frac{M^2}{4}}\,(\sigma L - \sigma L\,\sigma N +$$

$$+ \sigma N) - 2N\sqrt{N - \frac{N^2}{4}}\,\sigma N - \left(\frac{h}{R}\cot\varphi - M\right)^2 (1 - \sigma L)(1 - \sigma N)\Big]\,\sigma M +$$

$$+ \Big[\frac{S_0}{2}\left(1 + \frac{h}{R}\cot\varphi + \cot\varphi\, L\,\sigma L\right) - S_0\left(1 - 2N\sqrt{N - \frac{N^2}{4}}\,\sigma N\right)\Big] \times (1 - \sigma M), \tag{1}$$

Moreover, we assume that: $Q \stackrel{\text{def}}{=} \frac{S_0}{W}$ is the relative cloud cover of the target area, /38

$$M \stackrel{\text{def}}{=} 2 + \frac{H}{R}\cot\varphi - \frac{l}{R},$$

$$N \stackrel{\text{def}}{=} 2 - \frac{H}{R}\cot\varphi,$$

$$L \stackrel{\text{def}}{=} \tan\varphi - \frac{h}{R},$$

where

$$\sigma: \sigma_{(x)} = \begin{cases} 1, & \text{if } x > 0 \\ 0, & \text{if } x \leq 0, \end{cases}$$

H is the average cloud bottom altitude,

h is the average cloud thickness,

L is the average distance between cloud centers,

R is the average cloud radius,

S_0 is the area of clouds within the target,

ϕ is the sun height above the local horizon during the survey time,

W is the area of the target.

The quantity M indicates the degree of coverage by clouds of shadows of neighboring clouds and N, the degree of coverage by clouds of their own shadows. The sign of the argument is positive when the clouds cover shadows and negative, when the clouds do not cover the corresponding shadows. The quantity L indicates whether the shadows have an elliptical or circular shape.

Formula (1), despite its bulk, still does not take certain cases into account, for example, the appearance of shadows cast by clouds on the images of neighboring ones at a very low sun height and the like. However, this and similar cases occur outside the limits of accuracy of the approximation, and they can be disregarded.

For simplification of use, formula (1) can be presented in the form of a table (Table 1), by limiting values of the characteristics: the ratios of sun height (ϕ) to relative cloud thickness (H/R) (left row headings of the table), by the ratio of the average distance between clouds (L-2R) to the distance between the centers of clouds and their shadows (H cot ϕ) (column headings of the table) and by the ratios of the cloud sizes (2R) to the distance between the centers of the shadows and clouds (H cot ϕ) (right row headings of the table). Actual cloud structure measurements are the initial data: R, S_0, L, partially h and H, from local space photographs (similar to those which were obtained from the manned space craft Soyuz-9 and the Salyut manned orbital station), h and H, from hydrometeorological station data and atmospheric probes (where they exist), and ϕ from tables of the sun height above the local horizon and the space survey time.

From the data listed in the appropriate column of Table 1, the fraction of participation of the shadows cast can be calculated in the model of sporadic cloudiness, approximating the shapes of cumulus clouds. The characteristics are grouped in Table 1 in six initial dimensionalities (Fig. 1). The right column of the table (Fig. 1.1), at H cot ϕ < 2R indicates that a portion of the shadows is covered by

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TABLE 1
PRACTICAL FORMULAS FOR CALCULATION OF ADDITIONAL TARGET COVERAGE AS A CONSEQUENCE OF SHADOWS CAST BY CLOUDS (S_+)

	$l-2R > H\cot\varphi$ $(M<0)$	$l-2R < H\cot\varphi$ $(M<0)$	
$\tan\varphi > \frac{h}{R}$ $(L>0)$	$S_+^1 = S_0$ $\sigma L=1$ $\sigma M=0$ $\sigma N=0$	$S_+^5 = S_0\left(1-\frac{M}{2}\sqrt{M-\frac{M^2}{4}}\right)$ $\sigma L=1$ $\sigma M=1$ $\sigma N=0$	$H\cot\varphi > 2R$ $(N<0)$
$\tan\varphi < \frac{h}{R}$ $(L<0)$	$S_+^2 = \frac{S_0}{2}\left(1+\frac{h}{R}\cot\varphi\right)$ $\sigma L=0$ $\sigma M=0$ $\sigma N=0$	$S_+^6 = S_+^5 - S_0\left(\frac{h}{R}\cot\varphi - M\right)^2$ $\sigma L=0$ $\sigma M=1$ $\sigma N=0$	
$\tan\varphi > \frac{h}{R}$ $(L>0)$	$S_+^3 = S_0\left(1-\frac{N}{2}\sqrt{N-\frac{N^2}{4}}\right)$ $\sigma L=1$ $\sigma M=0$ $\sigma N=1$	$S_+^7 = S_+^3 - S_0\frac{M}{2}\sqrt{M-\frac{M^2}{4}}$ $\sigma L=1$ $\sigma M=1$ $\sigma N=1$	$H\cot\varphi < 2R$ $(N>0)$
$\tan\varphi < \frac{h}{R}$ $(L<0)$	$S_+^4 = S_+^2 - S_0\frac{N}{2}\sqrt{N-\frac{N^2}{4}}$ $\sigma L=0$ $\sigma M=0$ $\sigma N=1$	$S_+^8 = S_+^4 - S_0\frac{M}{2}\sqrt{M-\frac{M}{4}}$ $\sigma L=0$ $\sigma M=1$ $\sigma N=1$	
	$N \overset{\text{def}}{=} 2 - \frac{h}{R}\cot\varphi$ $M \overset{\text{def}}{=} 2 + \frac{h}{R}\cot\varphi - \frac{l}{R}$	$l = \sqrt{\frac{\pi}{Q}}\,R$	

clouds and, at $H \cot \phi > 2R$ (Fig. 1.2), that the cloud shadows have /40
completely gone beyond the vertical projections of the clouds. The left column of the table, at $\tan \phi < h/R$ (Fig. 1.3) corresponds to quite thick clouds, in which the tops cast additional shadows and, at $\tan \phi > h/R$ (Fig. 1.4), to flat clouds, the tops of which at a given sun height do not cast shadows and, consequently, their thickness can be disregarded in the calculations. Finally, the most complicated gradation is represented by the upper row of the table, where, at $\ell - 2R > H \cot \phi$ (Fig. 1.5), with equally probable distribution of clouds, the shadows of neighboring clouds do not overlap and, at $\ell - 2R < H \cot \phi$ (Fig. 1.6), are covered by neighboring clouds. As a result, eight squares are distinguished in the table grid, which characterize the following relationships of cloud cover (S_0) and shadow (S_+):

The clouds do not cover any shadows, and the shadows have circular outlines (Table 1.1);

The clouds do not cover any shadows and the shadows have elongated outlines (Table 1.2);

The clouds partially cover their shadows, in which the shadows have circular outlines (Table 1.3);

The clouds partially cover their shadows, in which the shadows have elongated outlines (Table 1.4);

The clouds partially cover the shadows of neighboring clouds, in which the shadows have circular outlines (Table 1.5);

The clouds partially cover the shadows of neighboring clouds, /41
in which the shadows have elongated outlines (Table 1.6);

The clouds partially cover their shadows and the shadows of neighboring clouds simultaneously (Table 1.7, 1.8).

As a result of calculation of the additional coverage of the earth's surface by shadows cast by clouds, quantities, the values of which change significantly depending on sun height, were obtained (Fig. 2). In this case, the following initial cloud structure data were used: $H = 1$ km, $R \tan \phi > h$, $R = 1$ km, shape is isometric, dimensions are

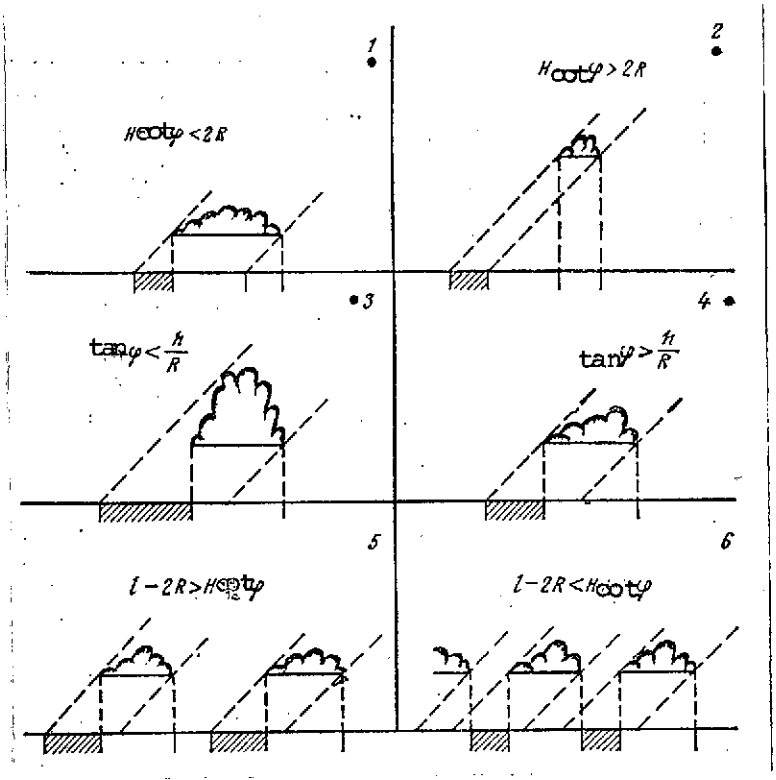

Fig. 1. Basic forms of the relationships of cloud cover of the earth's surface and the shadows cast by clouds in the model of sporadic cumulus clouds, as functions of its height, thickness and degree of coverage.

equidimensional, and distribution is equally probable, which corresponds in general to the static concept of good weather cumulus clouds with stable stratification of the atmosphere.

From an analysis of the calculated dependences of S_+ on ϕ and on S_0 (Fig. 2), the following conclusions can be drawn. With a sun height $\phi \geq 45°$, initially, with increase in cloud coverage, the additional coverage of the earth's surface by cloud shadows increases and reaches the maximum dimensions (23-17%), with a cloud cover of 40-60%. Then, with increase in cloud cover over 40-60%, in connection with overlapping of the shadows by the clouds themselves, the area of the visible shadows decreases to 0-13%. The role of the shadows in masking the underlying surface is particularly great at sun heights $\phi < 45°$. In this case, complete covering of the earth's surface with clouds and shadows can occur, even with moderate values of cloud cover of 40-60%, and additional coverage of targets, as a consequence of the shadows cast, can reach very high values, comparable with the cloud coverage proper, i.e., 40-60%.

Calculation of the effectiveness of the survey of the earth's surface from the spacecraft ERTS-1 took account of only the space-time distribution

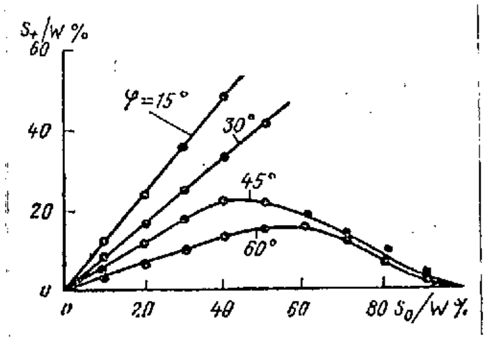

Fig. 2. Shape dependences of additional coverage of the earth's surface by shadows cast by clouds S_{+} on cloud cover S_0 and the sun height above the horizon ϕ.

of clouds. The sun-synchronous survey from the ERTS-1 spacecraft is conducted at about 9 hours 30 minutes local time at the latitude of the equator. This provides a sufficiently low sun height during the survey period, which facilitates better detail imagery of the mesorelief on the space images. However, at moderate cloud cover values, additional shadows noticeably mask the underlying surface in the spaces between clouds.

Thus, at a sun height of 30°, the coverage of targets by cloud shadows can reach 34% with a cloud cover of 40% or 42% with a cloud cover of 50%, and with a 60% cloud coverage and more, the earth's surface at this sun height is not scanned at all during the survey period. Based on what has been stated, allowing for the coverage with clouds and shadows cast by clouds, for a survey of the earth from a sun-synchronous spacecraft, an initial ϕ should be recommended for calculations, not of $\phi \sim 30°$, as was adopted in the recommendations for the ERTS-1 spacecraft, but $\phi \approx 45°$, which considerably decreases the dimensions of the visible shadows cast by clouds.

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